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Research paper

A new solution for loading optimization of multi-chiller systems by general algebraic modeling system

Elahe Salari, Alireza Askarzadeh*

Department of Energy Management and Optimization, Institute of Science and High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran

HIGHLIGHTS

- Optimal chiller loading is necessary for energy conservation.
- An efficient optimization method should be used for solving OCL problem.
- General algebraic modeling system (GAMS) is proposed to solve OCL problem.
- GAMS produces more promising results than the other existing methods.

GRAPHICAL ABSTRACT

1. Formulate the OCL as an optimization problem
2. Define objective function and constraints
3. Code the OCL problem in GAMS
4. Input the data into GAMS (power coefficients, cooling load, etc)
5. Solve the OCL problem using GAMS solvers
6. Return the result of GAMS as the optimal PLR of the chillers

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ABSTRACT

In hot and humid regions, due to the limitation of peak power, it is vital to reduce the electrical power consumption of multi-chiller systems since their consumption noticeably increases if the chillers are improperly managed. For this aim, optimal chiller loading (OCL) is one of the most important issues in such systems. The ultimate aim of the OCL problem is to determine the partial load ratio (PLR) of each chiller with respect to the cooling load demand. Owing to the nonlinearity of the OCL problem, a powerful search method should be employed to efficiently solve this problem. In this paper, general algebraic modeling system (GAMS) has been proposed to solve OCL problem. GAMS is an efficient and easy to implement high level computer programming language for modeling and solving optimization problems (linear, nonlinear and mixed integer). In order to evaluate the efficiency of the proposed methodology, two case studies are solved and the results are compared with the results obtained by both conventional and heuristic search methods. The results represent that GAMS produces promising results in comparison with the other methods.

1. Introduction

In the hot and humid climates, it is preferable to employ air-conditioning systems for maintaining a comfort level of life. The energy consumption of an air-conditioning system is huge which leads to the rapid growth of power consumption during peak hours of the days in summer. In the heating, ventilating and air-conditioning (HVAC) system, chiller that is widely used to provide the cooling load, is one of the major equipments in energy consumption. In large buildings, multi-chiller systems are the central part, consisting of chillers with different performance characteristics and capacities to operate for meeting large cooling requirements. In such systems, optimal loading of the chillers for energy conservation during various cooling loads is very important.

* Corresponding author. Tel./fax: +98 342 6233176.
E-mail addresses: a.askarzadeh@kgut.ac.ir, askarzadeh_a@yahoo.com (A. Askarzadeh).

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Nomenclature

α_i	power coefficient of *ith* chiller
β_i	power coefficient of *ith* chiller
γ_i	power coefficient of *ith* chiller
ψ_i	power coefficient of *ith* chiller
COP	coefficient of performance
f_i^{power}	consumed power of *ith* centrifugal chiller
i	chiller number
Nc	total number of chillers
P_t	sum of the consumed power of the chillers
PLR	Partial Load Ratio of *ith* chiller
Q	nominal capacity of the chiller
QT	total cooling demand
u_i	ON/OFF status of *ith* chiller

In the multi-chiller systems, each chiller contributes to provide a part of the cooling load. With respect to its partial load ratio (PLR), each chiller consumes a power which is obtained by the power vs. PLR characteristic of the chiller. For a given cooling load, a group of chillers operate to provide the load. Hence, for energy conservation, the best combination of the chillers should be used. At this state, the sum of the power consumed by the chillers is minimal.

The ultimate aim of the optimal chiller loading (OCL) problem is to determine the PLR of a set of chillers to minimize the system power consumption and satisfy the cooling load, simultaneously. Study of the literature indicates that the OCL problem has been solved by both conventional and heuristic optimization methods, namely, Lagrangian method (LM) [1], equal load rate (ELR) [1], branch and bound (B&B) method [2], genetic algorithm (GA) [3], evolutionary strategy (ES) [4], simulated annealing [5], particle swarm optimization (PSO) [6], continuous genetic algorithm (CGA) [6], binary genetic algorithm (BGA) [6], artificial neural networks [7], neuro-evolutionary systems [8], dynamic programming (DP) [9], cuckoo search (CS) [10] and firefly algorithm (FA) [11].

In Ref. [1], the coefficient of performance (COP) has been selected as the objective function and the performance of two conventional methods is investigated. In this reference, the performance of Lagrangian method (LM) and equal load rate (ELR) has been compared and it has been concluded that LM has much less power consumption and good accuracy. In Ref. [2], branch and bound (B&B) method has been proposed to solve the OCL problem and eliminate the deficiencies of the conventional methods. B&B can get the optimal solution by use of operation research. Based on the demands and limits of the problem, it selects limited feasible solution nodes systematically and solves the problem with those feasible solutions under the given limits until they can no longer be branched to achieve the optimum solution. The results of this reference show that the B&B method consumes much less power than the maximal peak COP (MPCOP) method. In Ref. [3], genetic algorithm (GA) which is a heuristic technique inspired by the natural selection has been proposed to overcome this flaw that LM is not suitable since the OCL is a non-convex optimization problem. The results indicate that GA not only solves the problem, but also produces results with high accuracy within a rapid timeframe. With the aim overcoming the flaw of LM in handling non-convex problems, in Ref. [4] evolution strategy (ES) has been proposed to solve the OCL problem. ES is a heuristic technique based on ideas of adaptation and evolution. It has been reported that ES not only solves the problems of LM method and GA method, but also produces results with high accuracy within a rapid timeframe. In Ref. [5], it is attempted to solve the OCL problem by utilizing simulated annealing (SA) which is a heuristic optimizer based on annealing process in metallurgy. It is mentioned that SA eliminates the limitation that the LM cannot solve OCL because the kW-PLR curves simultaneously include convex functions and non-convex functions. This study fully addressed the load balance constraint and chiller operating limits. The results of this paper represent the effectiveness of SA in comparison with LM. In Ref. [6], the authors have used three heuristic methods to solve the OCL problem. These methods are binary genetic algorithm (BGA), continuous genetic algorithm (CGA) and particle swarm optimization (PSO). PSO is a population-based heuristic technique inspired by the social behavior of animals. Because of continuous nature of OCL problem, continuous GA is introduced as a new optimization method in solving the OCL problem. Results are compared with results of applying binary GA to OCL problem. It is said that PSO and continuous GA are strongly recommended methods for solving OCL problem. Cuckoo search (CS) [10] and firefly algorithm (FA) [11] are two other heuristic techniques that have been modified recently and applied to the OCL problem. The results of [10] and [11] indicate that using CS and FA based algorithms leads to obtaining more promising results than the other previous suggested methods, but it seems that in these investigations, the constraint related to the operating condition of the chillers by which each chiller should provide power more that 30 percent of its nominal capacity has been neglected. In Ref. [12], the author has applied a gradient-based method, named generalized reduced gradient, and then obtained better results when compared with other approaches. When two additional approaches (hybridization between meta-heuristic algorithm and gradient-based algorithm; and reformulation of optimization structure by adding a binary variable which denotes chiller's operating status) were introduced, generalized reduced gradient found even better solutions.

The main motivation of this paper is to provide a simple framework by which the OCL problem is efficiently solved. As a result, general algebraic modeling system (GAMS) which is an efficient and easy to implement tool is proposed for solving the OCL problem. GAMS includes various solvers to efficiently handle non-convex and nonlinear optimization problems. GAMS contains anintegrated development environment (IDE) and is connected to a group of third-party optimization solvers. Among these solvers are BARON,COIN-OR solvers, CONOPT, CPLEX, DICOPT, GUROBI, MOSEK, SNOPT, SULUM and XPRESS. In recent years, the capability of GAMS has led to its application in different areas such as optimization of the stack of a thermoacoustic engine [13], optimization of pump and valve schedules in water distribution system [14] and economic analysis [15].

The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization (linear, nonlinear and mixed integer). It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows the users to build large maintainable models that can be adapted quickly to new situations The GAMS language is formally similar to commonly used programming languages. In GAMS, models are described in concise algebraic statements which are easy for both humans and machines to read. Whole sets of closely related constraints are entered in one statement. A structure of GAMS program can be organized in three parts: data part, model part and solution part. Algebraic model formulations can be solved by a variety of commercial and noncommercial packages for linear, mixed integer, and nonlinear optimization problems. Since the environment of GAMS cannot be explained, more details can be obtained in Refs. [16,17].